Evaluation of a Statistical Refractivity Model using Observations from R/V PT SUR

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1. Background

Navy tactical decision aids, using the Advanced Propagation Model, provide very accurate radar and radio propagation assessments. Unfortunately, a trend of decreasing budgets has made fewer and fewer rawinsondes available. Additionally, even when sondes are available, ship or aircraft operations frequently preclude launching them. Naval meteorology and oceanography (METOC) officers and aerographer's mates (AG), especially those onboard aircraft carriers and those assigned to mobile environmental teams (MET), are called upon to provide radar and radio propagation support on a daily basis. Since they frequently have no upper air soundings upon which to base these assessments, there is a need for some other low-cost method of determining refractive conditions.

Other methods, such as Refractivity from Clutter (RFC), which extract atmospheric refractivity information from radars have shown promise. These algorithms, however, can only be run on ships equipped with the SPY phased array radar and communication of this data to METOC personnel on other ships remains a significant shortfall of the system.

The Pacific Missile Test Center conducted research to establish relationships from synoptic patterns and refractive conditions. A set of simple thumb rules was formulated describing conditions which are favorable to duct formation and a working model was developed for the North Atlantic and North Pacific basins. The algorithms for each basin are slightly different, but are very similar (Helvey and Rosenthal, 1-4). The author has written a FORTRAN program incorporating the Helvey and Rosenthal model which can be accessed via an internet web site.

2. Overview of the model

Refractive conditions depend upon the vertical distribution of temperature and humidity. Specifically, super-refraction or ducting usually occurs when temperature increases sharply with height and humidity decreases with height. Identifying the synoptic parameters which lead to these temperature and humidity conditions is key to identifying when ducting will occur.

The study found that ducting is almost twice as likely to occur when surface isobar curvature is anticyclonic than when it is cyclonic. Frequency of duct occurrence decreases with distance from a surface high and increases with distance from a front. Duct frequency increases significantly with increasing surface pressure. Duct occurrence is also related to quadrant of the high and increases with increasing stability, which is expressed in the model by the difference between surface and 700mb temperature (Helvey and Rosenthal, 10-17).

Similar relationships are established for estimating the height of the base of the duct. Duct thickness and strength are not estimated by this model (Helvey and Rosenthal, 18-19), but an attempt is made by this study to find any correlation between the model's assessment of duct occurrence probability and thickness or strength.

The model assigns point values based on observations of each of the synoptic parameters used. The sum of these points is divided by a sum of weighting factors to produce a single non-dimensional number. The larger this number, the greater the likelihood of duct occurrence. The output of the model is this likelihood categorized as unlikely, possible, probable, or very likely. The model also uses a logical sequence to estimate the duct height from synoptic parameters (Helvey and Rosenthal, 30-33). Figure 1 is an example of the model's output screen.

3. Evaluation method

Twenty-five rawinsondes were launched from the research vessel PT SUR between August 2, 2001 and August 8, 2001 over the North Pacific near central California. Three of these were tethered, three were flown on a kite at low altitudes, and six did not reach 700mb height. The remaining thirteen rawinsondes were used to evaluate this model.

Ducting is determined by the gradient of refractivity. Refractivity *N* is calculated by the equation:

$$N = \frac{77.6P}{T} + \frac{(3.73\times 10^{5})e}{T^{2}}$$

where *P* is pressure in millibars, *T* is temperature in Kelvin, and *e* is water vapor pressure in millibars. The gradient of N in the standard atmosphere is about -0.39m^{-1} and ducting occurs when gradient is less than or equal to -0.157m^{-1}. Therefore is convenient to define modified refractivity *M* as:

$$M = N + 0.157h$$

where *h* is height in meters. Now if M is vertical or has a negative gradient, ducting will occur (Helvey and Rosenthal, 5). The modified refractivity profile was calculated for each sounding and used to determine the observed ducts.

At the time of each rawinsonde launch surface pressure, air temperature, wind direction (for determining quadrant of high), sea surface temperature, cloud and haze observations, and actual height of cloud base were observed. Curvature of surface isobar, distance to nearest high, distance to nearest front, and existence of offshore flow were determined from ETA model analyses. Presence and appearance of stratus clouds were determined from GOES-10 satellite imagery. Finally, the 700mb temperature was extracted from the soundings. In operational use of the model, this value would be obtained from an atmospheric model, but the rawinsonde value was used in the experiment in order to ensure that inaccuracies in another model do not affect the evaluation of the refractive conditions model.

In order to simplify the evaluation process, the four categories of probabilities must be somehow transformed into a positive and negative assessment. For this experiment, assessments of “unlikely” and “possible” were defined as negative (no duct present) and assessments of “probable” and “very likely” were defined as positive (duct present). The model outputs the estimated duct height as a single height value or a range of heights so these can be directly compared to the observed height of the duct. For assessments of a range of heights, the model was considered correct if the observed height fell within the range the model estimated. For those cases where only a single value for height was output, the model was considered correct if the observed value fell within 15% of the model’s value.

Four combinations of assessment and observation can occur. These combinations are illustrated in the table below.

1 Duct assessed Duct observed	2 Duct assessed No duct observed
3 No duct assessed Duct observed	4 No duct assessed No duct observed

Combinations 1 and 4 are counted as successful assessment by the model and combinations 2 and 3 are unsuccessful. Figure 2 provides a summary of the model-determined values and the observed values used in the study. Figures 3 through 9 are the modified refractivity profiles showing observed ducts in each case evaluated. In these figures the modified refractivity profile is plotted in blue and the observed duct is plotted in red.

This experiment provided the opportunity to evaluate only a small number of all possible cases. Since ducts were observed in all cases, only combinations 1 and 3 were possible. All cases evaluated were in the North Pacific; the North Atlantic model was not evaluated. Finally, all cases evaluated were located in the southeastern quadrant of the subtropical high.

4. Accuracy of determining duct occurrence

The model assessed duct occurrence as “probable” in five cases and “very likely” in eight cases. In each of these cases, the modified refractivity profile showed that ducts did exist, though most ducts were very weak. While the model produced the correct assessment in every case evaluated, it certainly cannot be said that the model is one hundred percent accurate. The sample size is not statistically significant, all cases were in the same quadrant of the high, and the model was only evaluated in cases in which a duct actually occurred. Therefore, the only reasonable evaluation must be qualitative. The model appears to be very accurate in assessing duct occurrence in cases where a duct occurs in the southeastern quadrant of the subtropical high.

5. Accuracy of determining duct height

The model was a complete failure at determining duct height. In only one of the thirteen cases was the correct height determined. This equates to only 7.7% accuracy. In one other case the model estimated duct height as 2000m when the observed height was 2374m. Still this represents an incorrect assessment, as the difference is 16 percent. Most frequently, 76.9% of the time, the model predicts the duct height significantly too low. In fact, in six cases the model predicted surface-based ducts though none were actually observed. In two cases, 15.4% of the time, the model predicted ducts which too high.

The model estimated an average duct height of 478m while the average observed height was 786m, a difference of 39 percent. While the number of cases evaluated do not represent a statistically significant sample, it is reasonable to state that the model shows no skill in estimating duct height under the conditions observed in this experiment.

High winds could have contributed to this underestimation of duct height. Since wind speed is not accounted for by the model, increased mixing due to the wind could have resulted in a higher than normal boundary layer which is not reflected in the other parameters used. Also if the sea surface temperature observation were colder than the surrounding region the height underestimation problem would be compounded.

6. Correlation of duct occurrence probability with duct thickness

Though never suggested by Helvey and Rosenthal, the author considered the possibility that there may be some correlation between higher model probability of duct occurrence and thickness of the duct. A higher probability of occurrence simply means that a greater number of factors favorable to duct occurrence exist. It seems reasonable to suggest that the more favorable conditions are for formation, the thicker the duct that will form. Thus one would expect to observe thicker ducts when the model predicts "very likely" than when it predicts "probable".

This suggested correlation appears not to exist. When the model predicted "probable", the observed duct thickness ranged from 133m to 430m with an average of 266.2m. When the model predicted "very likely", the observed thickness was 113m to 317m with an average of 190.9m. While there is not enough evidence to establish that a negative correlation exists, one may conclude that this data does not support a positive correlation.

7. Correlation of duct occurrence probability with duct strength

Since a higher probability of duct occurrence means that more conditions favorable for duct formation exist, there might also be some correlation between the model's duct occurrence probability and duct strength. The strength of the duct is determined by the difference between the maximum and minimum modified refractivity in the duct. If this difference is larger, electromagnetic rays will be refracted more, and therefore the duct is stronger.

One would expect that the environments determined "very likely" would have stronger ducts than those determined "probable". The experiment showed that the environments determined “probable” had a mean duct strength of 17.0 with a range from 8 to 34. The “very likely” environments had a mean strength of 11.4 and a range of 3 to 26. These similarities in both mean and range indicate that there is no correlation.

8. Recommended changes to the model

The most important improvement needed in the model is the duct height estimation algorithm. While the model seems quite capable of inferring duct occurrence, it has very little skill at estimating the height of the duct. Extensive research is needed to determine which synoptic parameters, if any, can suggest the height of a duct and then developing a set of thumb rules which can be incorporated into the model to more accurately estimate the duct height. It should be noted, however, that all ducts observed in this study were quite weak and the model may work much better when stronger ducts occur.

The difference between the surface temperature and the 700mb temperature is used as a measure of stability by the model. The difference between surface air temperature and sea surface temperature is likely to be a better stability parameter for two reasons. First, though the observed rawinsonde 700mb temperature was used in this study, in operational use this observation would not be available. In the absence of an observed value, a forecasted temperature from an atmospheric model would be used and any errors in the atmospheric model could cause inaccuracies in the refractivity model. Since surface air temperature and sea surface temperature are both easily measured, using this difference would not provide the opportunity for atmospheric model errors to enter the refractivity model. Additionally, considering the temperature at two levels as far separated vertically as the surface and 700mb may not adequately account for a shallow inversion layer which could cause ducting.

The model does not consider wind speed. High wind speeds, such as those encountered during this cruise, can cause greater mixing and result in a deeper boundary layer. Since many other parameters may still indicate a shallower layer, the model will estimate a duct height that is too low.

The sea surface temperature value used by the model in estimating the duct height is a single point observation. If the observation is located over a small scale temperature anomaly, an inaccurate duct height estimation can occur. Using an average value for sea surface temperature from satellite imagery for some region of interest may provide more accurate estimations of duct height.

Additional evaluation is necessary for a wider range of atmospheric refractive conditions. In order to determine reliable accuracies, evaluation must be conducted which includes observations in all quadrants of the subtropical high, in environments including weak and strong ducts and in environments where ducts do not occur. Finally, testing must be conducted in the North Atlantic basin as well.

9. Conclusions

A definitive accuracy cannot be established based upon only thirteen observations. These observations all occur in the southeastern quadrant of the subtropical high in the North Pacific basin and in all cases, weak ducts were observed. Under these conditions, the model appears to be very accurate in determining duct occurrence. However, the height estimates do not appear to be trustworthy and there is no obvious correlation between the model's probability of duct occurrence and duct thickness or strength.

References

Helvey, R.A. and J. S. Rosenthal, 1983: Guide for inferring refractive conditions from synoptic parameters. Technical Report, Pacific Missile Test Center, 36pp.

Estimation of Refractive Conditions

This program categorizes the probability of ducting, from least probable to most probable, as follows:

- UNLIKELY
- POSSIBLE
- PROBABLE
- VERY LIKELY

The results for this case are:

Ducting is VERY LIKELY.

If there is a duct, expect the base at

800. meters (2624. feet).

Return for another case

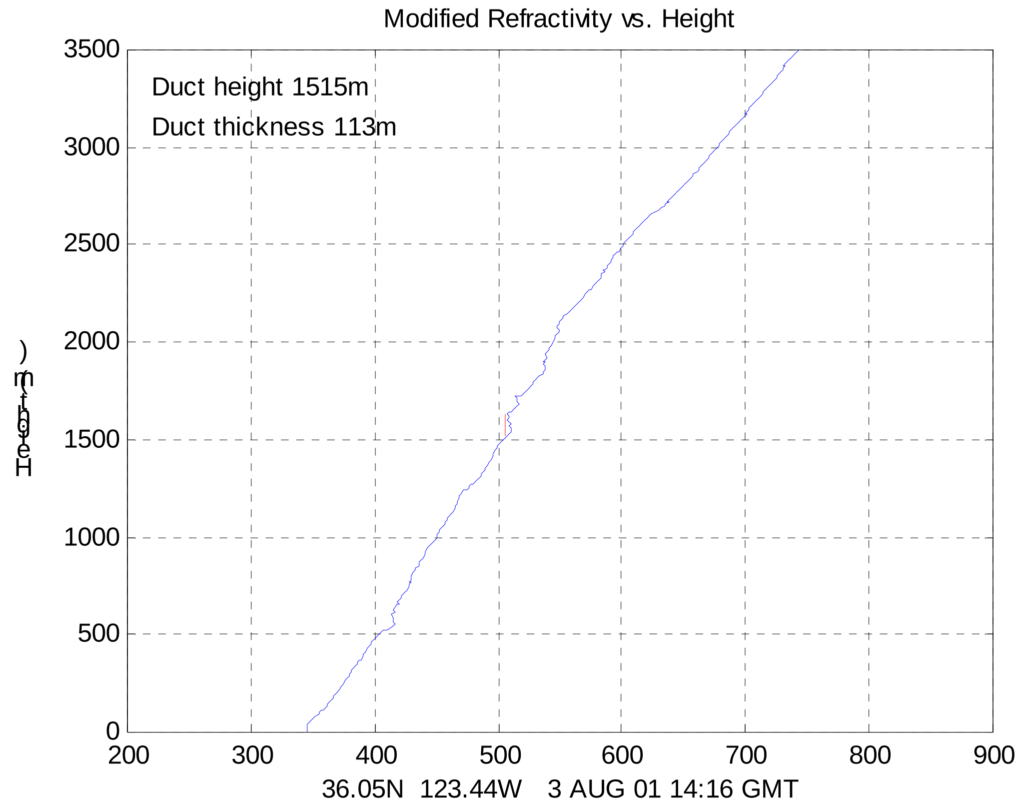
Figure 1

Data Summary

	2Aug01/1754	2Aug/2057	3Aug/1416	4Aug/0609	4Aug/1434	5Aug/1425	6Aug/0138	6Aug/1324	6Aug/2046	7Aug/0159	7Aug/1754	7Aug/2355	8Aug/0131
Likelihood	Probable	Probable	Very Likely	Very Likely	Very Likely	Very Likely	Probable	Very Likely	Very Likely	Very Likely	Very Likely	Probable	Probable
Predicted height	0-3m	0-3m	0-81m	0-300m	0-116m	800m	2000m	0-10m	0-300m	0m	0m	800m	1800m
Actual height	215m	123m	1515m	1955m	993m	1801m	2374m	297m	246m	133m	72m	256m	235m
Actual thickness	430m	430m	113m	155m	113m	235m	164m	123m	154m	317m	317m	133m	174m
Duct strength	23	34	3	7	5	7	10	7	13	23	26	8	10

Figure 2

M Profiles when Model Determined Ducting "Very Likely"



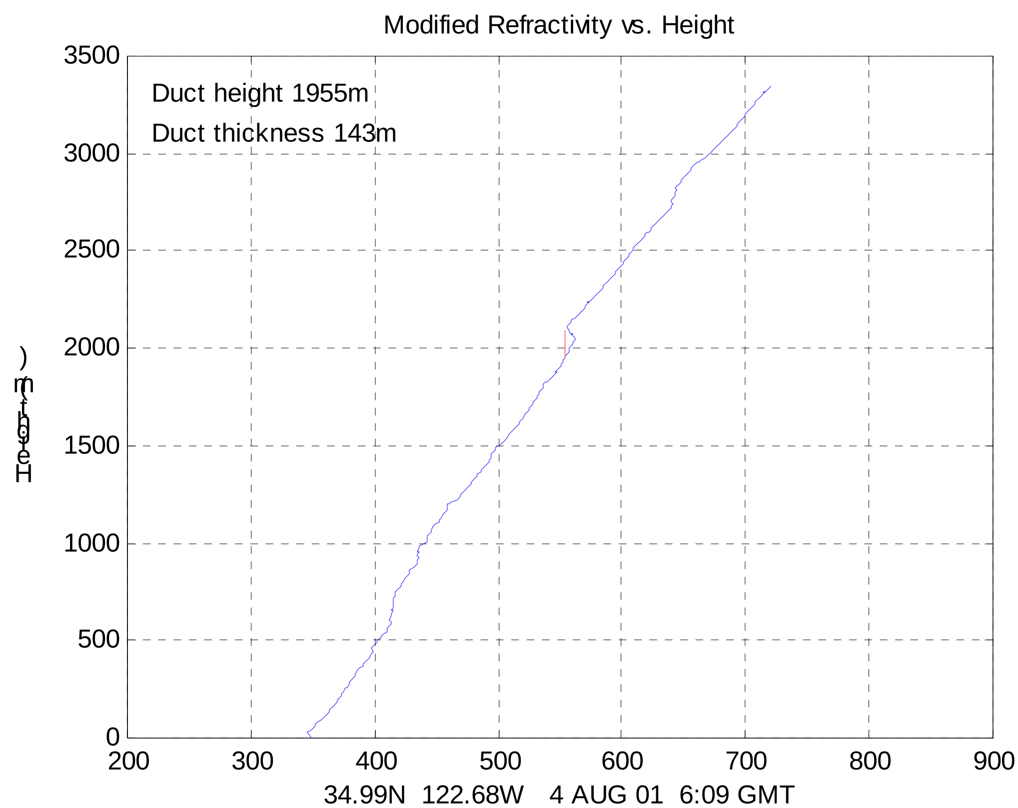
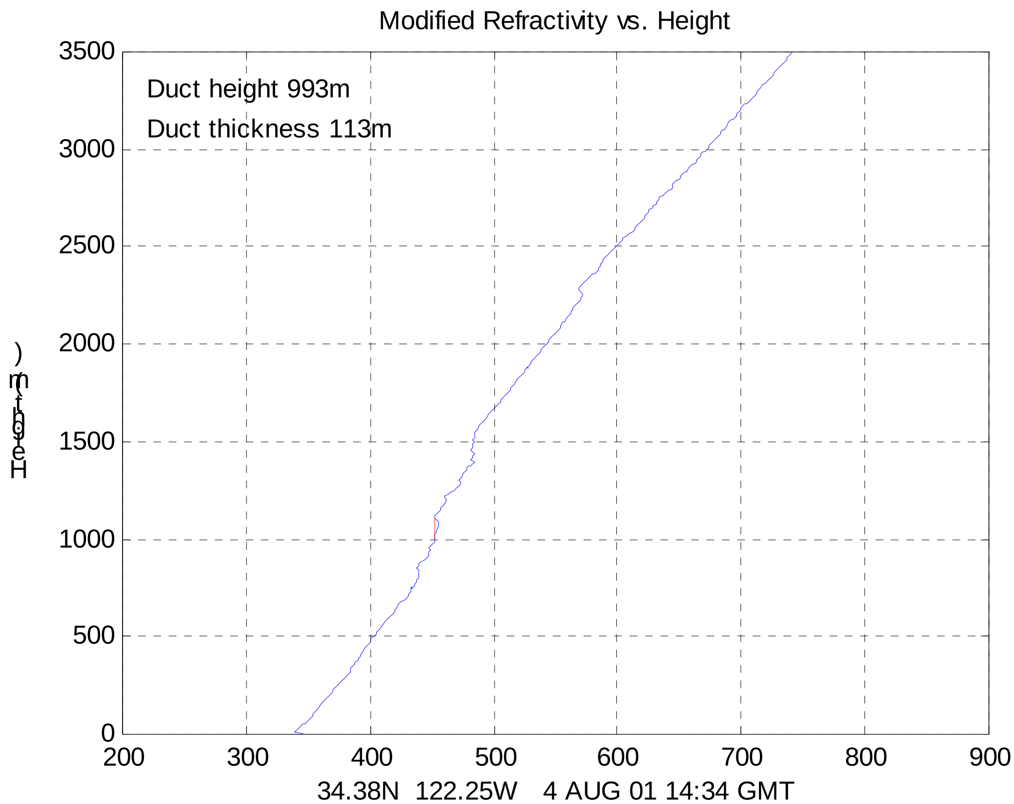


Figure 3

M Profiles when Model Determined Ducting "Very Likely"



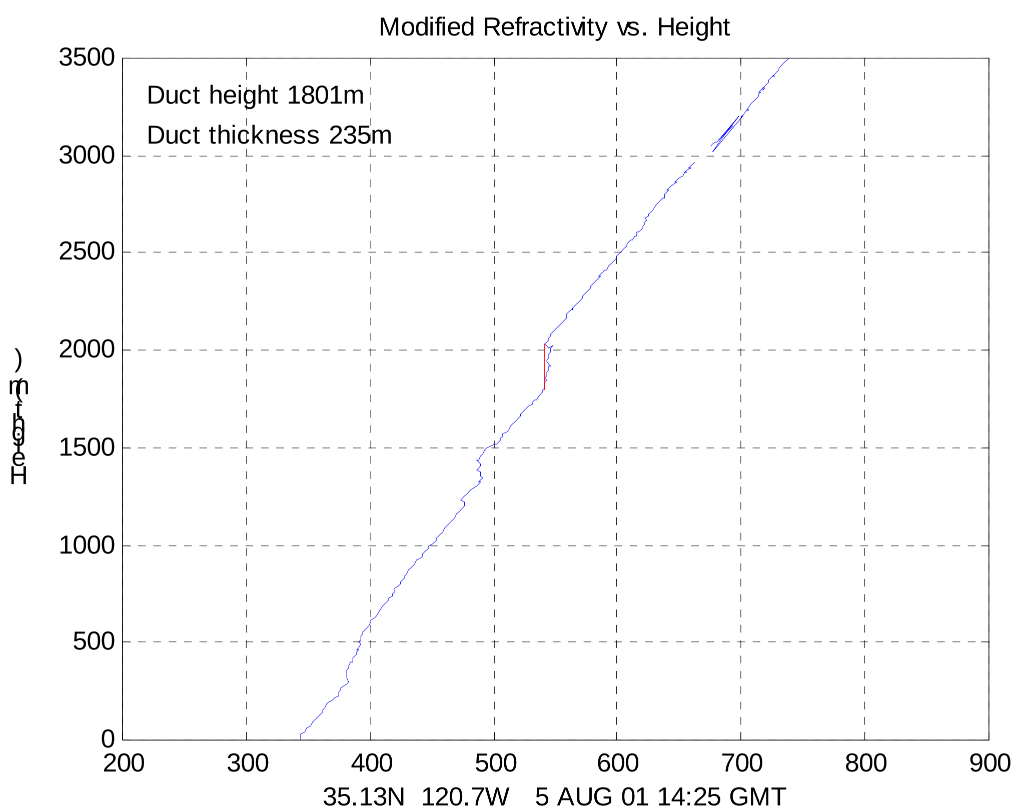
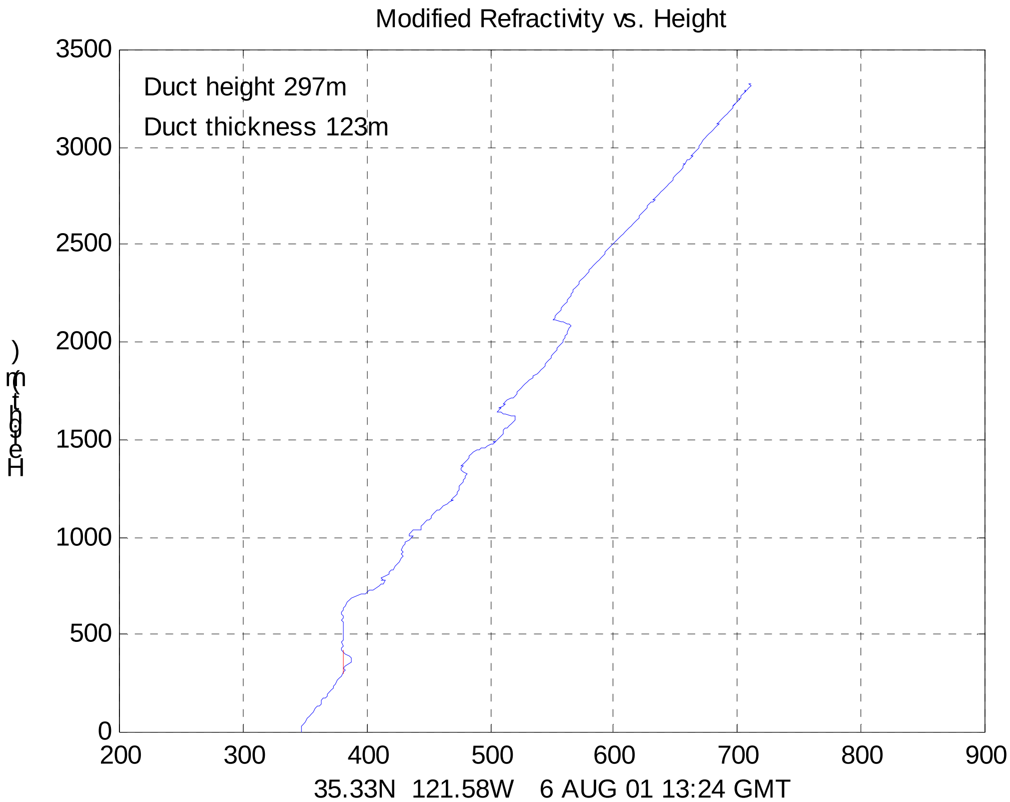


Figure 4

M Profiles when Model Determined Ducting "Very Likely"



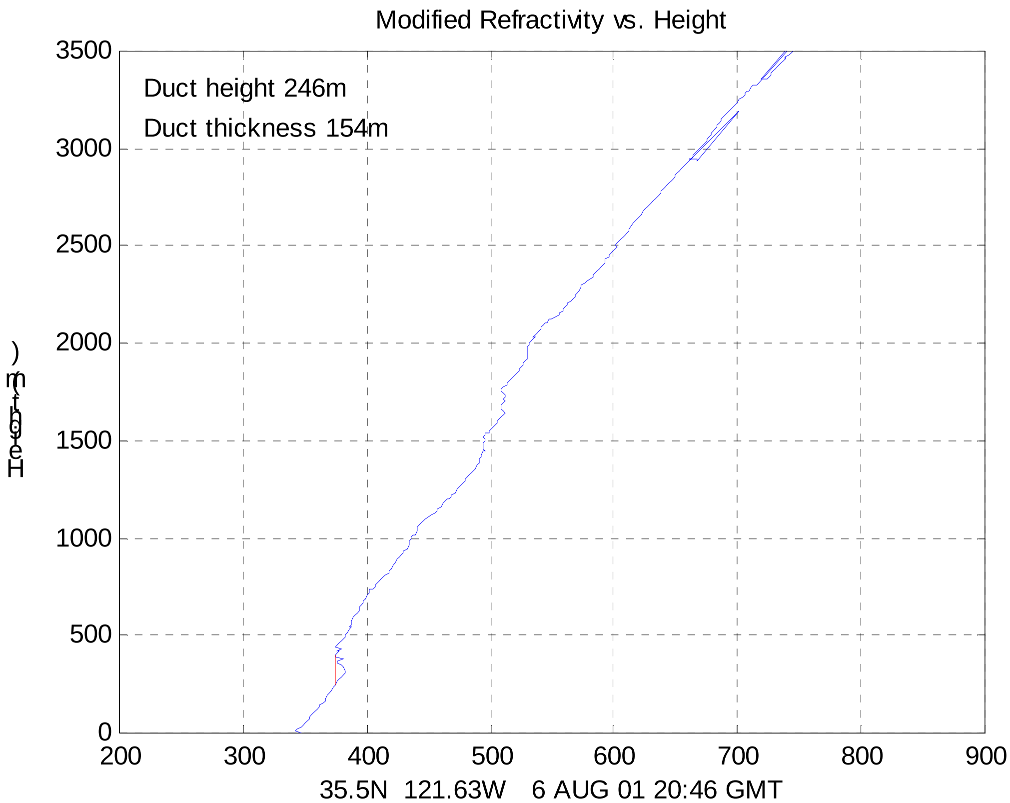
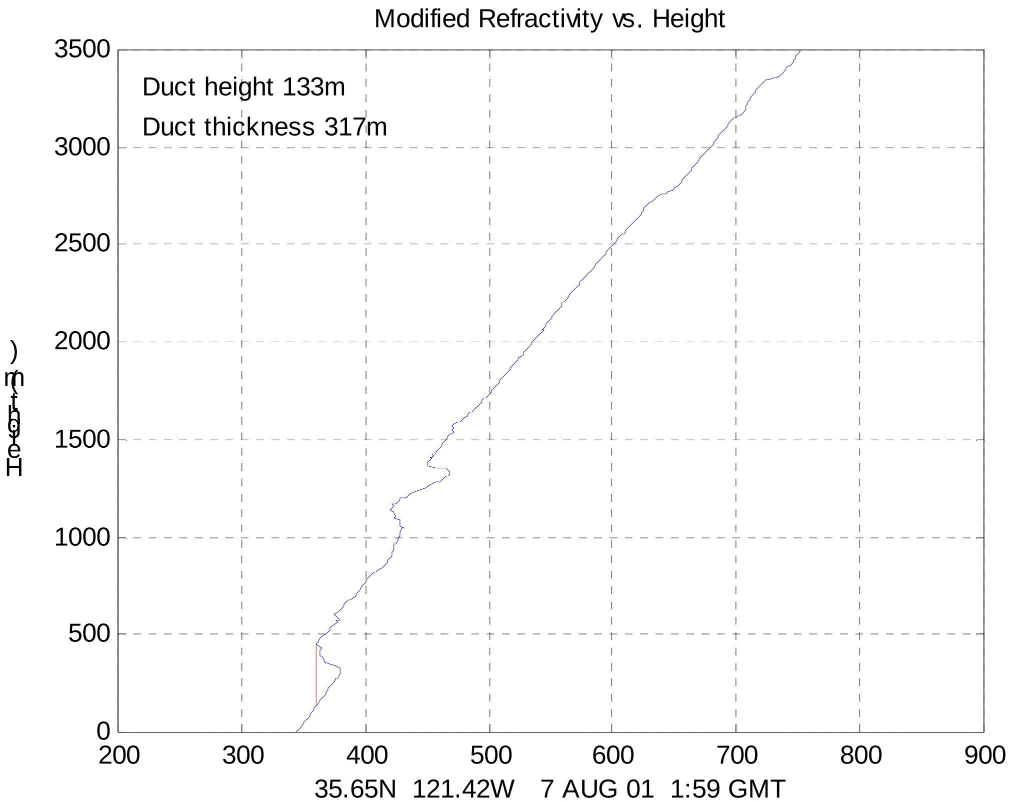


Figure 5

M Profiles when Model Determined Ducting "Very Likely"



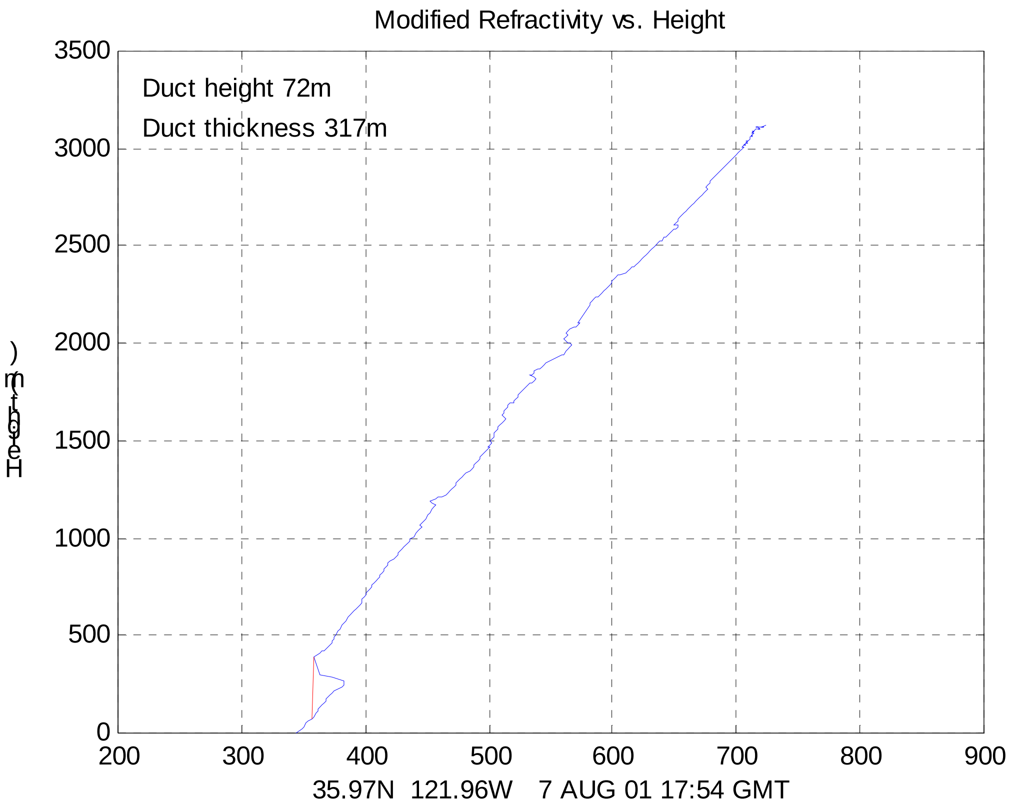
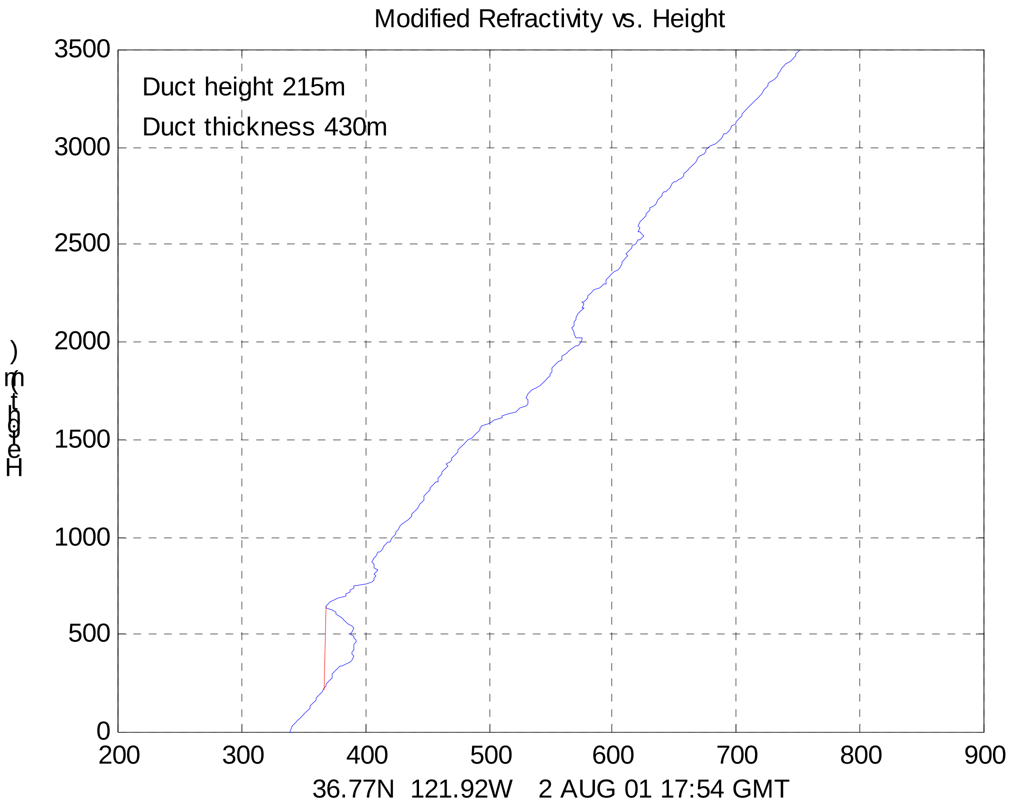


Figure 6

M Profiles when Model Determined Ducting "Probable"



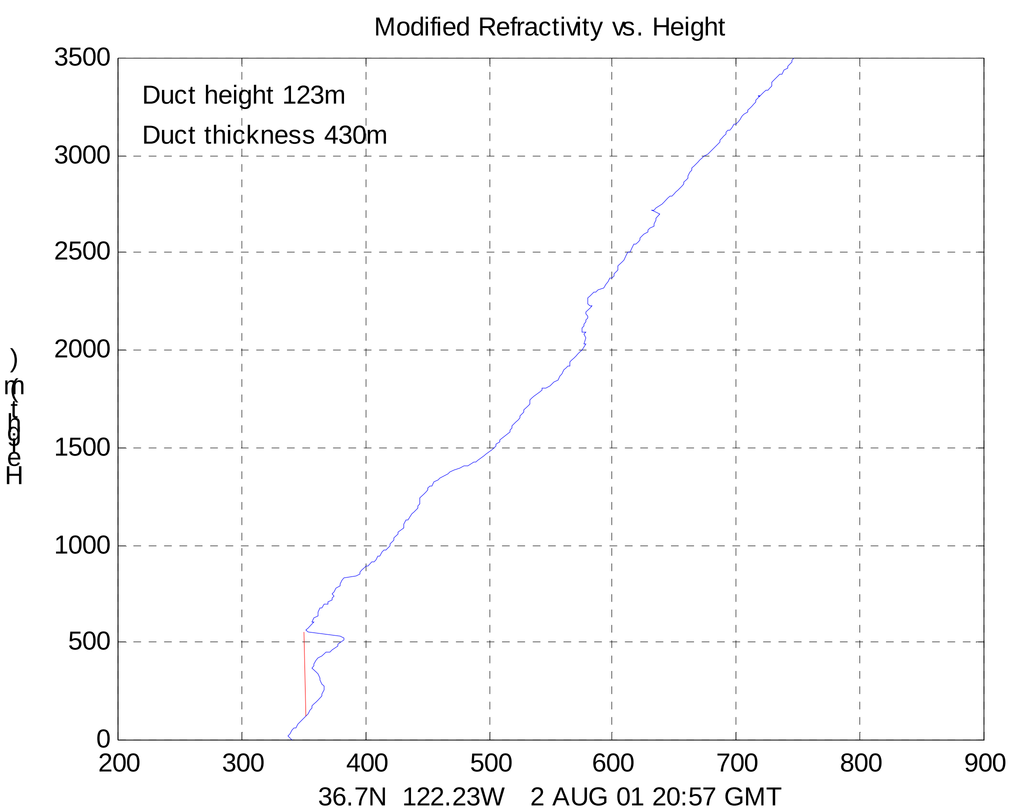
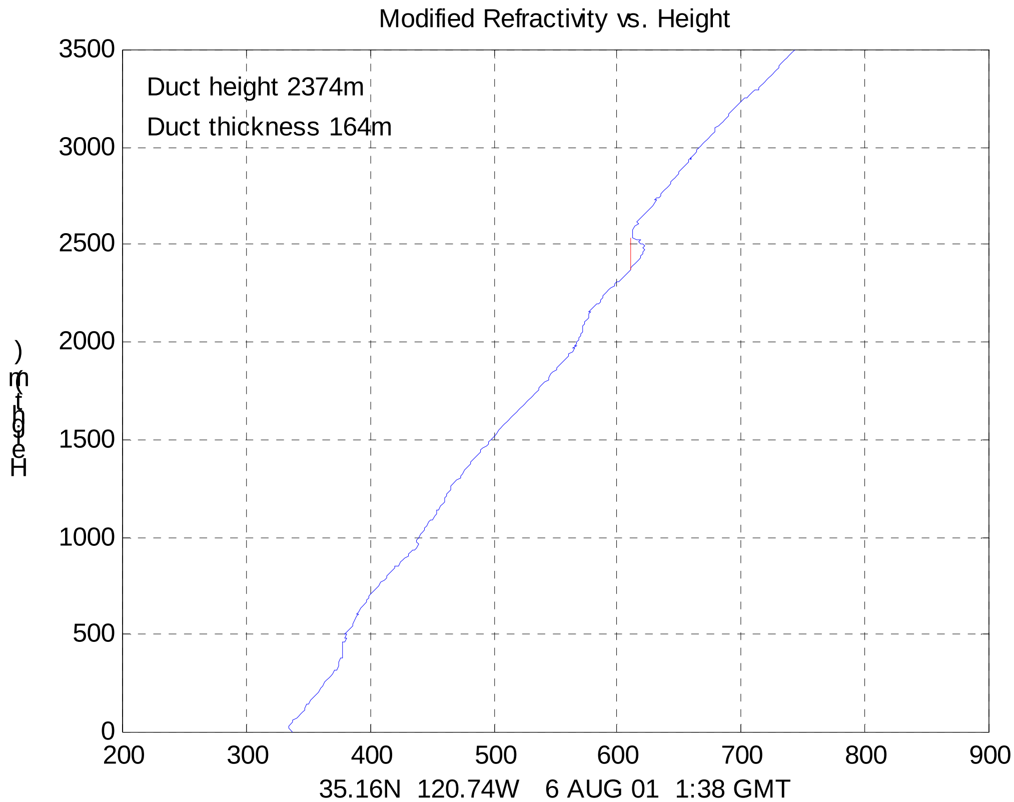


Figure 7

M Profiles when Model Determined Ducting "Probable"



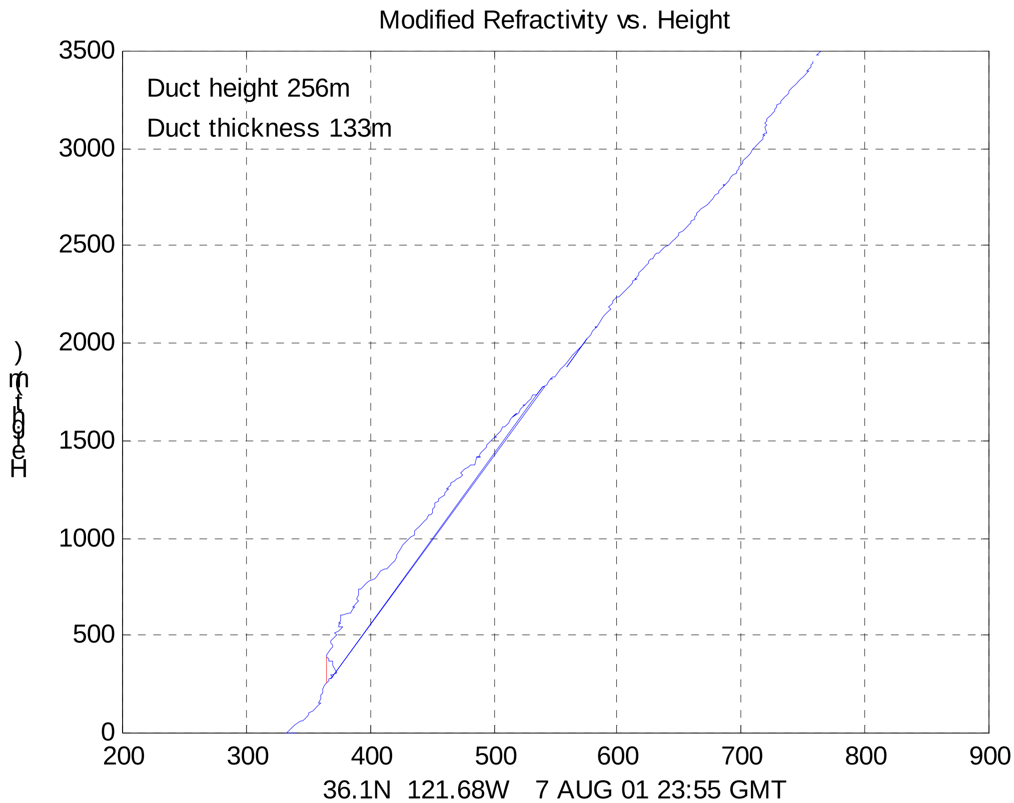


Figure 8

M Profiles when Model Determined Ducting "Probable"

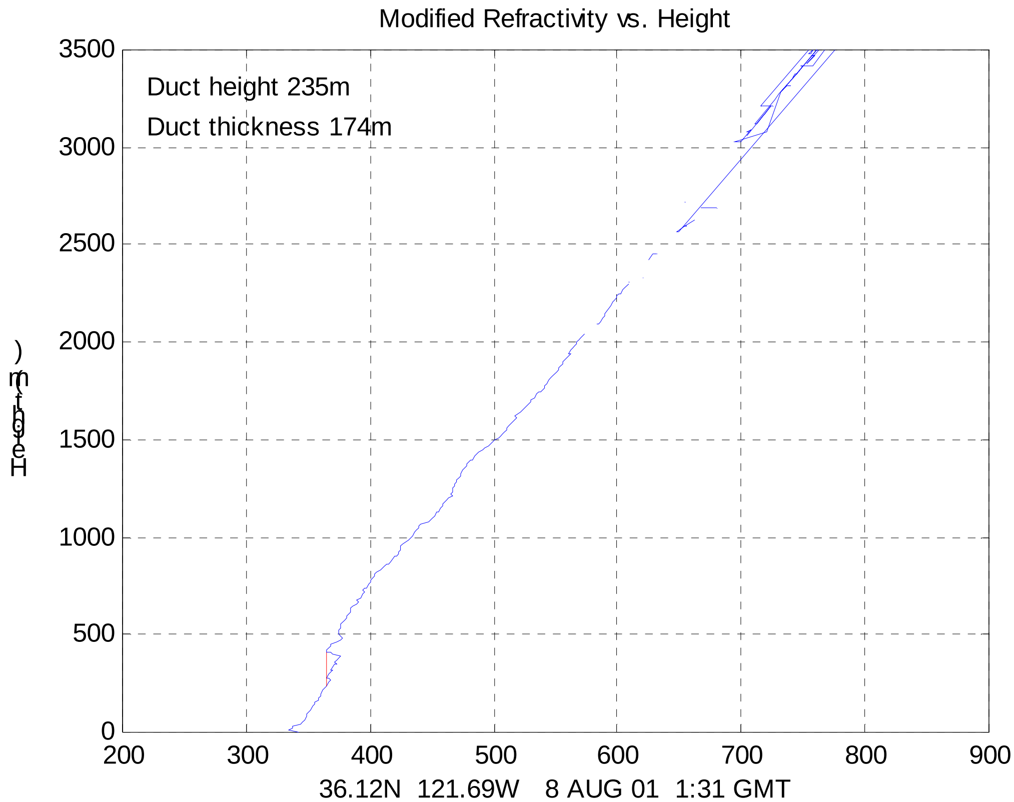


Figure 9